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Climate change impact on the ecological status of rivers: The case of Albaida Valley (SE Spain)

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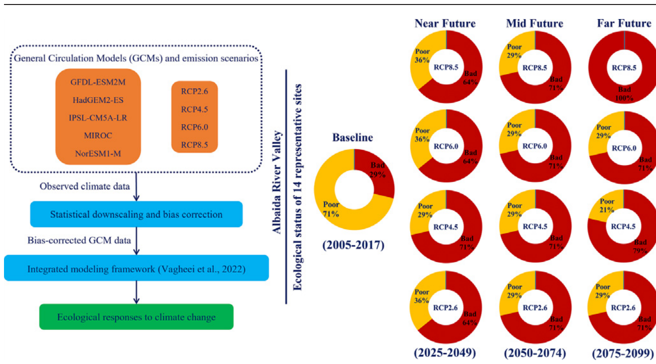
HIGHLIGHTS

- A recently presented modeling framework is employed in different scenario simulations.
- Climate change impact on ecological status is investigated.
- Climate change influences hydrology, water quality, and ecological status.
- In certain representative sites, ecological status is expected to downgrade.
- Scientifically informed decisions are essential to manage and protect freshwaters.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the effects of environmental stressors (e.g., potential changes in climate and land use) on ecological status is essential for freshwater management. The ecological response of rivers to stressors can be evaluated by several physico-chemical, biological, and hydromorphological elements as well as computer tools. In this study, an ecohydrological model based on SWAT (Soil and Water Assessment Tool) is used to investigate climate change impact on the ecological status of Albaida Valley Rivers. The predictions of five General Circulation Models (GCMs) each with four Representative Concentration Pathways (RCPs) are employed as input to the model for simulating several chemical and biological quality indicators (nitrate, ammonium, total phosphorus, and the IBMWP (Iberian Biological Monitoring Working Party) index) in three future periods (Near Future: 2025–2049, Mid Future: 2050–2074, and Far Future: 2075–2099). Based on chemical and biological status predicted with the model, the ecological status is determined at 14 representative sites. As a result of increased temperatures and decreased precipitations from most of GCMs projections, the model predicts decreased river discharge, increased concentrations of nutrients, and decreased values of IBMWP for future compared to the baseline period (2005–2017). While most representative sites have poor ecological status (10 sites with poor ecological status and four sites with bad ecological status) in the baseline, our model projects bad ecological status for most representative sites (four sites with poor ecological status and 10 sites with bad ecological status) under most emission scenarios in the future. It should be noted that the bad ecological status is projected for all 14 sites under the most extreme scenario (i.e., RCP8.5) in the Far Future. Despite the different emission scenarios, and all possible changes in water temperature and annual precipitation, our findings emphasize the urgent need for scientifically informed decisions to manage and preserve freshwaters.

1. Introduction

A variety of ecosystem services including provisioning services (e.g., irrigation and power generation), regulatory services

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(e.g., maintenance of water quality), cultural services (e.g., recreation and tourism), and supporting services (nutrient cycling and ecosystem resilience) are provided by freshwaters (Aylward et al., 2005). However, climate change, that is one of the most severe environmental issues, constitutes a menace to global freshwater sources (UN-Water, 2020). While past and current global warming has impacted freshwater resources and caused significant changes in their communities, the risks of biodiversity loss due to future climate change are expected to be even greater (IPCC, 2022).

Addressing and managing the effects and challenges posed by climate change on freshwater environments, requires a holistic and fundamental understanding of linkages between climate, hydrology, water quality, and biodiversity. These connections can be studied by integrating water quality monitoring and modeling (Holguin-Gonzalez et al., 2013; Vagheei et al., 2022). Water quality monitoring, that encompasses the collection of information on various biological, physico-chemical, and hydromorphological components of water resources (e.g., macrophytes, macroinvertebrates, nutrients, turbidity, and river discharge), is a useful tool for the detection of water pollution, the determination of ecological status, and the management and restoration of freshwater environments (Strobl and Robillard, 2008; Canter, 2018). In addition, the integrated modeling approaches can supplement the data obtained from field monitoring by producing reliable predictions of freshwater ecosystems responses to different climate scenarios (Guse et al., 2015; Carr et al., 2019).

Recent model-based studies predict that climate change can affect hydrological components (e.g., streamflow and evapotranspiration) (Goodarzi et al., 2020; Mahmoodi et al., 2021; Tarekegn et al., 2022), water quality variables (e.g., nutrient loads) (Povilaitis et al., 2018; Shrestha et al., 2018), and aquatic communities (e.g., abundance and diversity of fish and macroinvertebrates species) (Guse et al., 2015; Kakouei et al., 2018; Theodoropoulos and Karaouzas, 2021) of river watersheds. Climate change would likely exacerbate the frequency, duration, and severity of droughts as it has been reported in Africa by Ahmadalipour et al. (2019), in Aragon (NE Spain) by Gaitán et al. (2020), and in the Miyun Reservoir Watershed (China) by Qiu et al. (2023) that may be associated with the increased concentration of nutrients due to the reduction of water sources (Whitehead et al., 2006; Charlton et al., 2018). Climate change would also intensify extreme rainfall events as it has been reported over different climate regions by Tabari (2020) and across the U.S. by Moustakis et al. (2021) that may result in increased surface runoffs carrying more nutrients to water bodies (Andersen et al., 2006; Shrestha et al., 2012). Reduced river flow, higher level of nutrient concentration, excessive nutrient loading, and higher temperature caused by climate change then would impact freshwater habitat and biodiversity as it has been reported in the Tehuacán-Cuicatlán Biosphere Reserve (Mexico) by López-López et al. (2019) and in the Athabasca River Basin (Canada) by Morales-Marín et al. (2019).

Even though previous studies predict a detrimental effect of global warming on rivers (Jun et al., 2010; Lutz et al., 2019), the relationship between climate change and ecological status is still largely unexplored in many river watersheds. Therefore, this study uses the integrated modeling framework presented by Vagheei et al. (2022) to investigate possible impact of climate change on ecological conditions of the Albaida Valley Rivers (SE Spain), which, to the best of our knowledge, this valley has not previously been studied under possible future climate change scenarios. This study follows the Water Framework Directive (WFD) 2000/60/EC, that is the main legislation for achieving good ecological status in Europe, to specify the ecological status of the rivers. According to the WFD, the estimation of the overall ecological status is based on the status of biological quality elements (i.e., macroinvertebrates, diatoms, macrophytes, and fish) and supporting quality elements (i.e., physico-chemical and hydromorphological) (Tueros et al., 2009; Zacharias et al., 2020). The concept behind the WFD 2000/60/EC is the "One Out-All Out" (OOAO) principle, that assumes the final ecological status to be the worst status of the quality elements employed in the assessment (Zacharias et al., 2020). In the present work, the future ecological status of 14 representative sites along the rivers of the valley is predicted based on long time continuous projections of several chemical and biological indicators including nitrate, ammonium, total phosphorus, and the IBMWP (Iberian Biological Monitoring Working Party) index (a well-known macroinvertebrate-based metric) under several climate scenarios. Although the ecological status is generally assessed with more than one biological group, the macroinvertebrate community (the IBMWP index) is only used in this work as data on fish, diatoms and macrophytes were not available. However, macroinvertebrates are by far the most used and reliable biological group for biomonitoring, sometimes the only group that is used for river biomonitoring (Birk et al., 2012; Bo et al., 2017; Vitecek et al., 2021). In addition, the choice of this work is to isolate the effects of climate change on the Albaida Valley, and other factors such as demographic change, land use change, socioeconomic development, and changes in environmental strategies, which are important for optimal management of watersheds, are thereby not included. In fact, while the increased demand for water, energy, and food due to population and economic growth (Fader et al., 2016; Wang et al., 2019) leads to land use changes with respect to urbanization, industrialization, agriculture intensification, and deforestation (Aghsaei et al., 2020; Lei et al., 2022) and may increase the deterioration of freshwater ecosystems (Tzanakakis et al., 2020; Peña-Angulo et al., 2021), the aim of the present work is to understand how the processes induced by climate change can impact river water quality. The chosen approach in the present work allows quantifying and characterizing the uncertainties from both the model and the future climate projections, which has been discussed as a crucial step for watershed modeling and climate change impact assessments (Deser et al., 2012; Abbaspour et al., 2015). In fact, this study considers the model prediction uncertainty using the Sequential Uncertainty FItting version 2 (SUFI-2) algorithm and deals with uncertainties associated with future climate projections using ensemble modeling, that is the implementation of several climate models and emission scenarios.

2. Materials and methods

Climate change scenarios are simulated to assess the impact of changing future conditions on ecological status of the Albaida Valley (Spain). For this purpose: (1) Predictions of General Circulation Models (GCMs) are statistically downscaled, and bias corrected with the observed climate data; (2) the bias-corrected GCM data are coupled to the ecohydrological modeling framework proposed by Vagheei et al. (2022) to evaluate the ecological responses of Albaida Valley to climate change. Fig. 1 shows the overall methodology applied in the study, which is explained in detail in the next sections.

2.1. Study area and data description

A shrubland and agricultural dominated part of the Albaida Valley (Spain) with an approximate area of 320 km^2 is studied (Fig. 2). The Albaida Valley, which is characterized by a semi-arid Mediterranean climate, consists of the Clariano (P1-P9, Fig. 2) and Albaida Rivers (P10-P14, Fig. 2). The behavior of the Albaida River differs upstream and downstream of the confluence with the Clariano River (P13, Fig. 2) as it receives important contributions from the Clariano River that is severely affected by the effluents of WasteWater Treatment Plants (WWTPs). A few kilometers downstream of their confluence, the Albaida River flows into the Bellús Reservoir which is one of the most eutrophic reservoirs in the Valencian Community. A complete description of the area can be found in Vagheei et al. (2022).

In addition to data used for developing the ecohydrological model of the valley (Vagheei et al., 2022), the daily precipitation, and minimum and maximum temperature of five GCMs and four Representative Concentration Pathways (RCPs) with a resolution of 0.5° supported by ISI-MIP5 (Inter-Sectoral Impact Model Intercomparison Project) (Hempel et al., 2013) collected from https://www.2w2e.com and the daily observed precipitation, and minimum and maximum temperature data with a resolution of 5 km from the Spanish National Meteorological Service (AEMET) collected from https://swat.tamu.edu are also used (Table 1). The observed climatic data are used for downscaling and bias correction of the GCM results. Table S1 in the Supplement provides general information on the locations of the climatic data obtained from the monitoring stations and the GCMs.

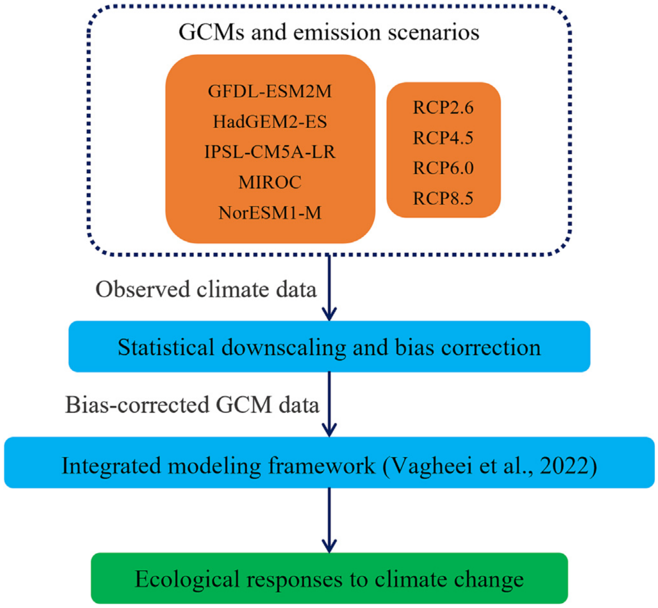

Fig. 1. Overview of the methodology applied in this study.

2.2. Uncertainty in climate change impact assessments

The assessment of climate change effects on river watersheds is accompanied with uncertainties from both the watershed model (e.g., uncertainties associated with the model input and the model structure) and climate projections (e.g., uncertainties associated with GCMs, emission scenarios, and downscaling and bias correction methods) (Kundzewicz et al., 2018; Tang et al., 2019). As previous studies found conflicting results about the relative importance of the uncertainty associated with climate projections compared to the hydrologic model uncertainty (Bennett et al., 2012; Sellami et al., 2016), characterizing uncertainty from both climate projections and the model is important for climate change impact assessments (Deser et al., 2012; Abbaspour et al., 2015). Thus, outputs of five GCMs including GFDL (US), HadGEM (UK), IPSL (FR), MIROC (JA), and NoerESM (NO) each with four carbon emission scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) are used in the present work, as ensemble modeling is recommended in several studies to deal with uncertainties associated with climate projections (Semenov and Stratonovitch, 2010; Teutschbein and Seibert, 2012; Perez et al., 2014; Shen et al., 2018). In addition, the SUFI-2 algorithm is used to characterize the model prediction uncertainty as it is capable of implementing all model uncertainties on the parameters (Abbaspour et al., 2015). In SUFI-2, 500 model realizations are simulated and the propagation of the uncertainty in parameters leads to the model prediction uncertainty which is quantified by the 95 % prediction uncertainty (the 95PPU). The 95PPU is calculated from the 2.5 % and 97.5 % quantiles of cumulative distribution of output variables generated through Latin hypercube sampling (Abbaspour, 2015).

2.3. Preparation of future climate data

GCMs, which are three-dimensional numerical models that represent the physical dynamics of the atmosphere, ocean, cryosphere, and land surface, have been developed to project how these systems would behave under possible future greenhouse gas (GHG) and aerosol forcing (IPCC, 2013). Projections from GCMs, which are time series of climatic data such as precipitation and temperature, are the best available data that could be used as input to ecohydrological models to simulate the effects of climate change on water resources, nutrient loading, biodiversity, ecosystems, and, eventually, to improve watershed decision-making and

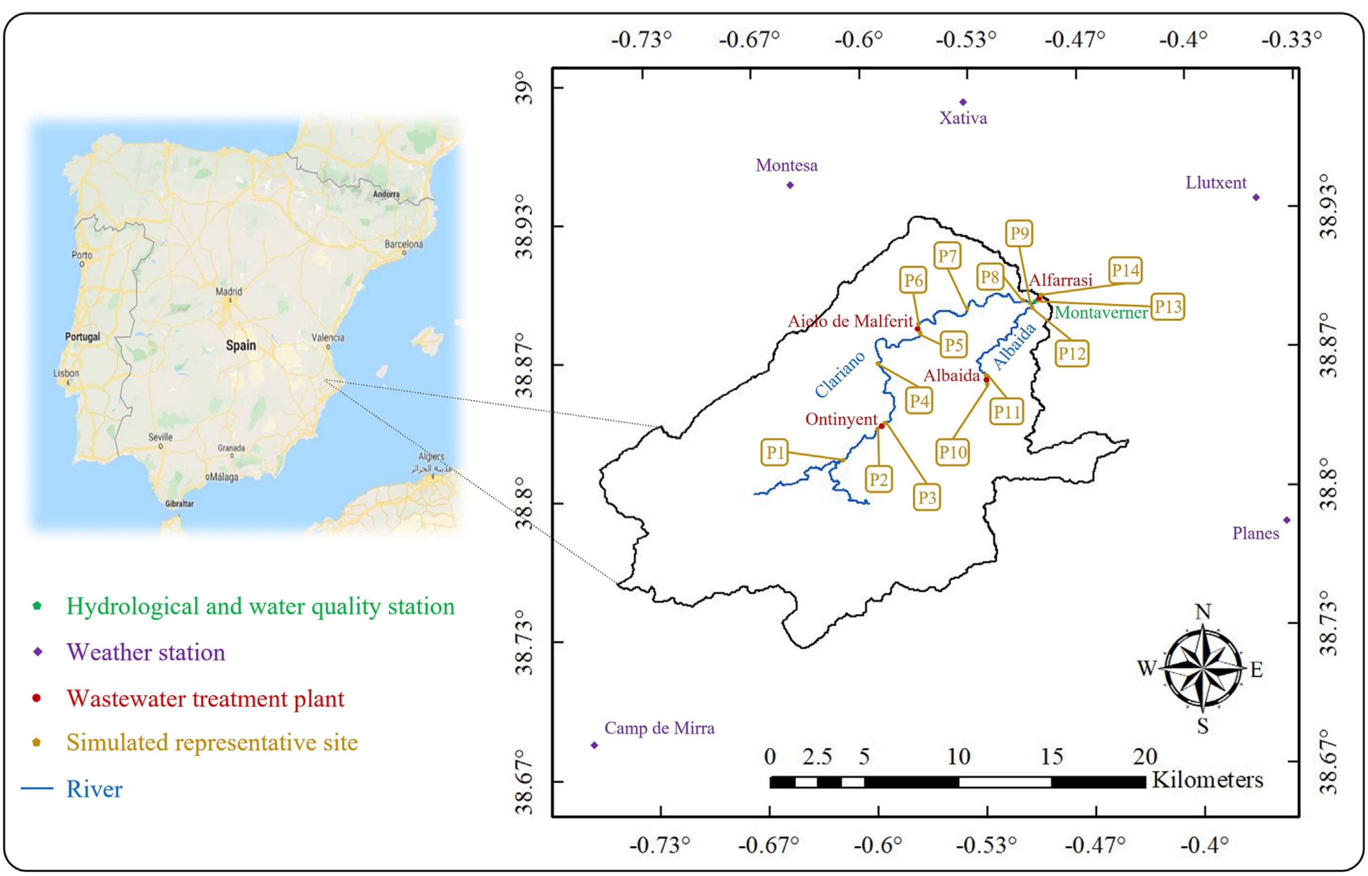

Fig. 2. Location of the study area, hydrological, water quality and meteorological stations, WWTPs, and representative sites simulated with SWAT (Soil and Water Assessment Tool).

Table 1
Overview of climate data used in this study. GFDL-ESM2M: Geophysical Fluid Dynamics Laboratory-Earth System Model version 2 M; HadGEM2-ES: Hadley Centre Global Environmental Model version 2-Earth System; IPSL-CM5A-LR: Institute Pierre Simon Laplace-Climate Model version 5A- Low Resolution; MIROC: Model for Interdisciplinary Research on Climate; NorESM1-M: Norwegian Earth System Model version 1 M (intermediate resolution).

Database	Model	Scenario	Period	Source
GCM1	GFDL-ESM2M	RCP (2.6, 4.5, 6.0, 8.5)	1951–2099	NOAA/Geophysical Fluid Dynamics Laboratory
GCM2	HadGEM2-ES	RCP (2.6, 4.5, 6.0, 8.5)	1951–2099	Met Office Hadley Center
GCM3	IPSL-CM5A-LR	RCP (2.6, 4.5, 6.0, 8.5)	1951–2099	L'Institut Pierre-Simon Laplace
GCM4	MIROC	RCP (2.6, 4.5, 6.0, 8.5)	1951–2099	AORI, NIES and JAMSTEC
GCM5	NoerESM1-M	RCP (2.6, 4.5, 6.0, 8.5)	1951–2099	Norwegian Climate Center
Observed data			1951–2005	AEMET (Spain)

management (Bouraoui et al., 2002; Park et al., 2013; Guse et al., 2015; Marcinkowski et al., 2017). The GCM data need to be downscaled and bias-corrected before being used in regional impact analyses as their spatial resolutions are generally too coarse and, furthermore, all GCM projections contain some biases that can result in significant errors, if not corrected (Teutschbein and Seibert, 2012; IPCC, 2013). Thus, the Climate Change Toolkit (CCT) (Ashraf Vaghefi et al., 2017) is used in this study to downscale and bias-correct the data of five previously mentioned GCMs for the study region. The toolkit identifies the measured data stations that are closest to the GCMs stations to apply the correction factor: for temperature, the "additive correction method" is employed, and for precipitation, the "ratio correction method" is used (Ashraf Vaghefi et al., 2017).

2.4. Projection of ecological status

In the present work, the ecological status of 14 representative sites (P1-P14, Fig. 2) is studied based on a successfully implemented SWAT-based model of the Albaida Valley River Basin (Vagheei et al., 2022). According to the WFD, the determination of the overall ecological status involves considering both biological quality elements (macroinvertebrates, diatoms, macrophytes, and fish) and supporting quality elements, which are physico-chemical and hydromorphological (Tueros et al., 2009; Zacharias et al., 2020). However, hydromorphological state is not commonly taken into account as a component of overall ecological status assessment for water bodies with an ecological status less than "high". Therefore, chemical and biological indicators are only used in this study. In addition, only the macroinvertebrate community is used among all biological indicators for assessing the biological status because of the lack of data on fish, diatoms and macrophytes.

To study the impact of climate change on river runoff and nutrient concentrations (concentrations of nitrate, ammonium, and total phosphorus), scenario runs based on the bias-corrected data of five GCMs under four carbon emission scenarios are compiled and analyzed with the SWAT model. The evaluation of ecosystem health in Near, Mid, and Far Future is then predicted with the IBMWP index (not only the most widely used index in Spanish Mediterranean rivers (Guareschi et al., 2017), but also the required index by the Spanish Royal Decree 817/2015), which was shown to be well correlated to nitrate concentrations (see Vagheei et al. (2022) for more details on this correlation). For this purpose, the SWAT model setup in the previous study (Vagheei et al., 2022) is updated as follows: (1) the Hargreaves method (Hargreaves et al., 1985) is used for estimating potential evapotranspiration instead of the Penman-Monteith method as GCM data consists only of precipitation and temperature data; (2) the land use map and agricultural management operations such as fertilization and irrigation are assumed not to change, and the average monthly effluent flow rates, and water quality data of WWTPs at baseline period (2005–2017) are used for simulation of future period (2025–2099); (3) monthly simulations are performed for both baseline and future periods (Near Future (2025–2049), Mid Future (2050–2074), and Far Future (2075–2099)). Since the model was already shown to perform adequately, the parameter ranges calibrated in Vagheei et al. (2022) are also used for the present work. The SUFI-2 algorithm provided in the SWAT-CUP (SWAT Calibration and Uncertainty Program) tool is used to generate 95PPUs (the 95 % prediction uncertainty) of discharge and concentrations of nitrate, ammonium, and total phosphorus for the baseline and future scenarios. Nitrate concentrations generated with the model are then coupled to the regression equation obtained in Vagheei et al. (2022) to produce the time series of IBMWP values. As described in Vagheei et al. (2022), this equation is resulted from the linear regression analysis between concentrations of nitrate and values of IBMWP resulting from sampling campaigns. Finally, the ecological status of rivers is determined based on projected chemical and biological status (using nitrate, ammonium, and total phosphorus as well as the macroinvertebrate community (the IBMWP index)) according to the Spanish Royal Decree 817/2015, that follows the "OOAO" principle. This principle is based upon the assumption that the worst status of the quality indicators used in the assessment determines the final ecological status (Zacharias et al., 2020). A complete description of the ecological status assessment can be found in Vagheei et al. (2022).

2.5. Quantification of uncertainties

Uncertainties of discharge, nitrate, ammonium, total phosphorus, and IBMWP projections are analyzed for the whole future period (2025–2099) to compare the contribution of three types of uncertainty, i.e., hydrologic parameter uncertainty (the differences between projections resulting from 500 SUFI-2 parameter solutions sets), GCM uncertainty (the differences between projections based on the use of five GCMs), and emission uncertainty (the differences between projections resulting from the use of four RCPs). For this purpose, projections are first averaged over time (900 months), and uncertainty analysis is then performed on these temporally averaged values as described below:

1. Hydrologic parameter uncertainty is quantified by averaging projected values over four RCPs and five GCMs and calculating the standard deviation over 500 (SUFI-2 parameter solutions sets) values.
2. GCM uncertainty is quantified by averaging projected values over four RCPs and 500 SUFI-2 parameter solutions sets and calculating the standard deviation over five GCMs values.
3. Emission uncertainty is quantified by averaging projected values over five GCMs and 500 SUFI-2 parameter solutions sets and calculating the standard deviation over four RCPs values.

3. Results and discussion

3.1. Projected temperature, precipitation, and discharge

Albaida Valley is expected to face rising temperature and reduced precipitation and discharge in all possible emission scenarios (Tables S2 and S3 in the Supplement). Detailed explanations of the projected temperature, precipitation, and discharge are provided in the Supplementary material.

3.2. Projected chemical indicators

95PPUs of chemical indicators of 14 representative sites were generated for baseline and future periods. Fig. S8 in the Supplement, as an example, shows the generated 95PPUs of nitrate load at the Site P14 for the baseline and the future (for GCM1 under RCP2.6 scenario). Simulated concentrations of nitrate, ammonium, and total phosphorus within the Albaida Valley

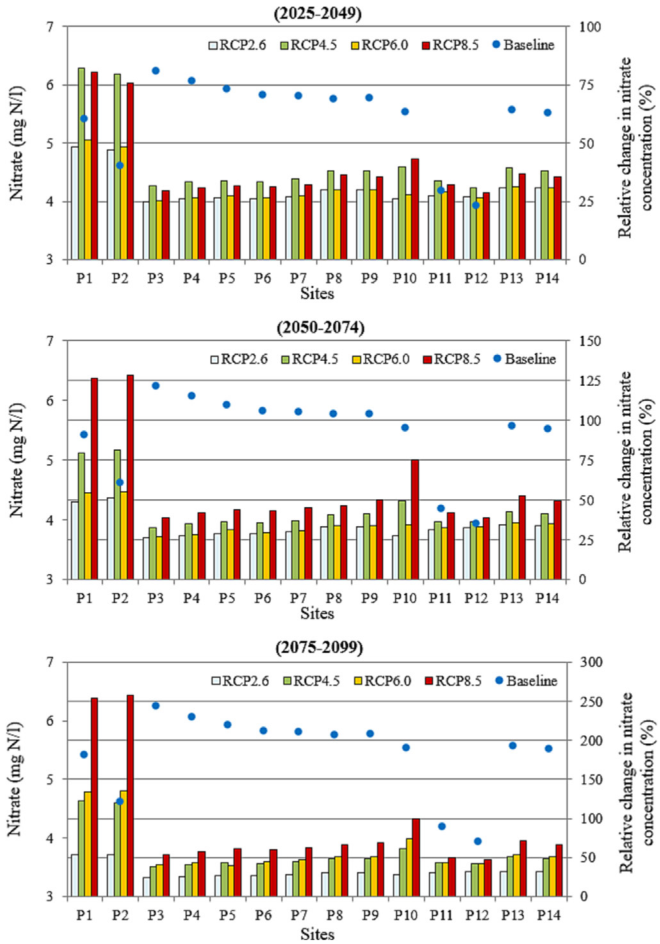

Fig. 3. Change in average nitrate concentration (%) at 14 representative sites compared to the baseline (2005–2017) using ensemble of five GCMs for the Near Future (2025–2049), Mid Future (2050–2074), and Far Future (2075–2099) for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios.

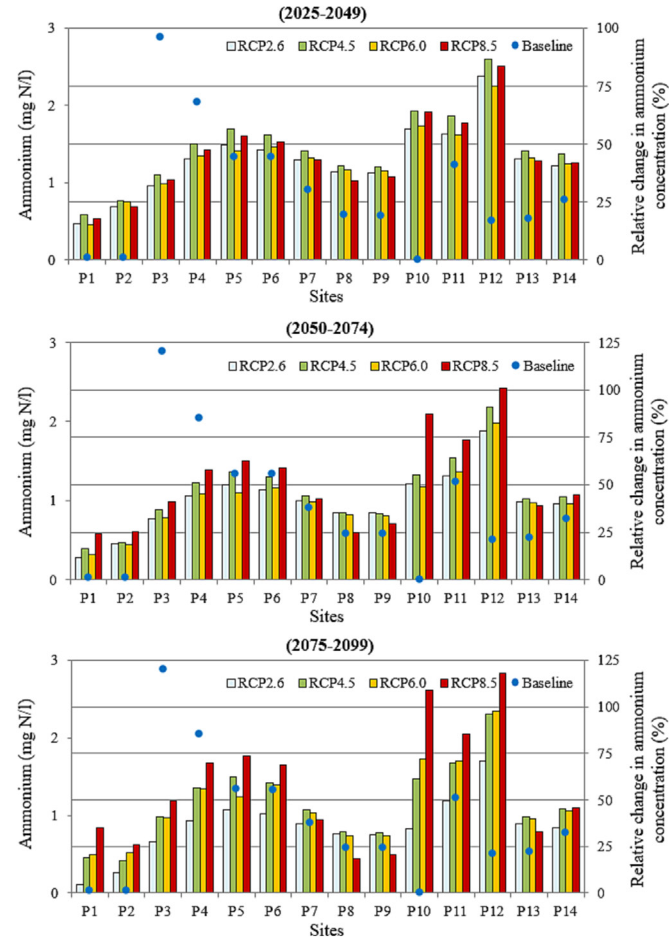

Fig. 4. Change in average ammonium concentration (%) at 14 representative sites compared to the baseline (2005–2017) using ensemble of five GCMs for the Near Future (2025–2049), Mid Future (2050–2074), and Far Future (2075–2099) for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios.

are projected to change in future compared to the baseline. According to the Figs. S9 to S13 in the Supplement, certain sites (i.e., Sites P1-P2, and P10-P12) have high variability of nitrate status (high uncertainty) in both baseline and future periods, where their nitrate status ranges from moderate to high. For the rest of sites (i.e., Sites P3-P9, and P13-P14), while nitrate status ranges from moderate to good in baseline period (mid variability), it is mostly moderate (low uncertainty) in the future. As Figs. S14 to S18 in the Supplement show, ammonium status of certain sites located in the upstream of rivers (i.e., Sites P1 and P2 in the Clariano River, and the Site P10 in the Albaida River) is always high (low variability) in both baseline and future periods. While for the rest of sites, ammonium status is mostly moderate with the probability of good and high status at some points, as well. Figs. S19 to S23 in the Supplement also represent that the total phosphorus status ranges from moderate and high at certain sites (i.e., Sites P1, P2, and P10). The average values are very representative for the rest of sites as uncertainty does not change too much and the total phosphorus status is moderate at these sites. Ensemble average nitrate concentration of 14 representative sites is projected to increase compared to the baseline period in all scenarios (Fig. 3). The most noticeable increases are found at P1, P2, and P10, where flow rates are low and hence less dilution is expected. Fig. 4 indicates that ensemble average ammonium concentration within the valley will likely increase compared to the baseline period in all sites. Ensemble average total phosphorus concentration within the valley is also predicted to increase compared to the baseline period along the streams of the valley apart from P1 and P2 (Fig. 5). These results are in agreement with predictions of changes in instream nutrient concentrations (Whitehead et al., 2006; Jeppesen et al., 2011), particularly with studies which suggest increases in riverine phosphorus and nitrogen concentrations (Arheimer et al., 2005; Kaste et al., 2006; Atkins, 2014; Molina-Navarro et al., 2014; Charlton et al., 2018). In fact, lower river flow under climate change reduces the dilution capacity of rivers, thereby resulting in higher concentrations of nutrients (Whitehead et al., 2006; Whitehead et al., 2009; Molina-Navarro et al., 2014; Charlton et al., 2018). Abily et al. (2021) discuss that climate change will lead to a dilution factor decrease for 11 % of the EU rivers. Baccour et al. (2021) also report the increased nitrate concentration and decreased water availability during droughts events in the Ebro River Basin (Spain), underlining the tradeoffs between quantity and quality of water. Using simulated concentrations and according to the Spanish Royal Decree 817/2015 and "OOAO" principle, moderate chemical status is predicted for all the representative sites in the future (Fig. 6), that emphasizes the evident need to control nutrient pollution.

3.3. Projected biological indicator

Values of IBMWP within the Albaida Valley are projected to change in future (Figs. S25 to S28 in the Supplement) compared to the baseline (Fig. S24 in the Supplement). As these figures indicate, the biological status, that ranges from bad to moderate at all the representative sites in the baseline period, remains bad to moderate at certain sites (i.e., sites P1-P2, and P10-P12) in the future, as well, and downgraded to the bad status (low uncertainty) at the rest of sites. Ensemble average IBMWP of 14 representative

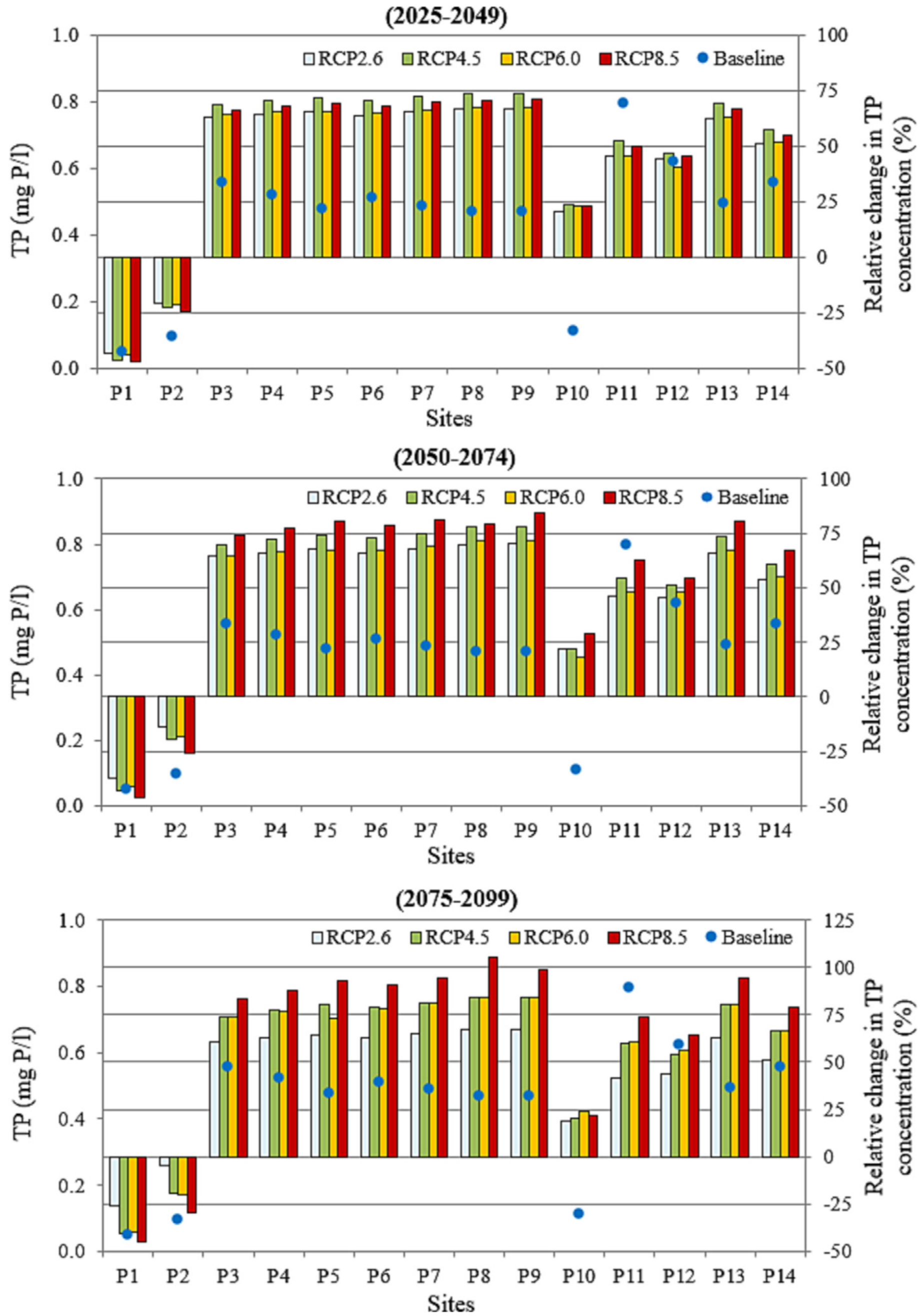

Fig. 5. Change in average total phosphorus concentration (%) at 14 representative sites compared to the baseline (2005–2017) using ensemble of five GCMs for the Near Future (2025–2049), Mid Future (2050–2074), and Far Future (2075–2099) for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios.

sites is predicted to decrease compared to the baseline period in all scenarios with highest decreases at sites that are already impacted (P3-P9; P13-P14) (Fig. 7). As expected, the highest reductions of IBMWP are projected for the most extreme scenario (i.e., RCP8.5). Using average values of IBMWP and according to the Spanish Royal Decree 817/2015, the biological status of certain representative sites may be downgraded from poor to bad status in the future (Fig. 8). The biological status of four representative sites (P3-P6) are classified as bad both in baseline and future periods. For the rest of representative sites (P1-P2; P7-P14) and under the RCP8.5 scenario, six sites (P7-P9; P12-P14) are expected to decrease their biological quality class in the Near and Mid Futures, while for the Far Future it is predicted that all 10 sites decrease their biological class and would be classified as bad. These results agree with other studies reporting that climate change may remarkably affect macroinvertebrates communities (Durance and Ormerod, 2007; Mantyka-Pringle et al., 2014; Kakouei et al., 2018). Therefore, the vulnerability of biodiversity to climate change should be reduced by conservation, protection, and restoration of freshwater ecosystems, as well as by targeted management to adapt to unavoidable effects of climate change (IPCC, 2022).

3.4. Quantified uncertainties

The quantified uncertainties for projected discharge (hydrologic parameter uncertainty: 0.07 m^3/s, GCM uncertainty: 0.08 m^3/s, and emission uncertainty: 0.04 m^3/s), nitrate (hydrologic parameter uncertainty: 0.58 mg N/l, GCM uncertainty: 0.42 mg N/l, and emission uncertainty: 0.37 mg N/l), ammonium (hydrologic parameter uncertainty: 0.11 mg N/l, GCM uncertainty: 0.05 mg N/l, and emission uncertainty: 0.02 mg N/l),

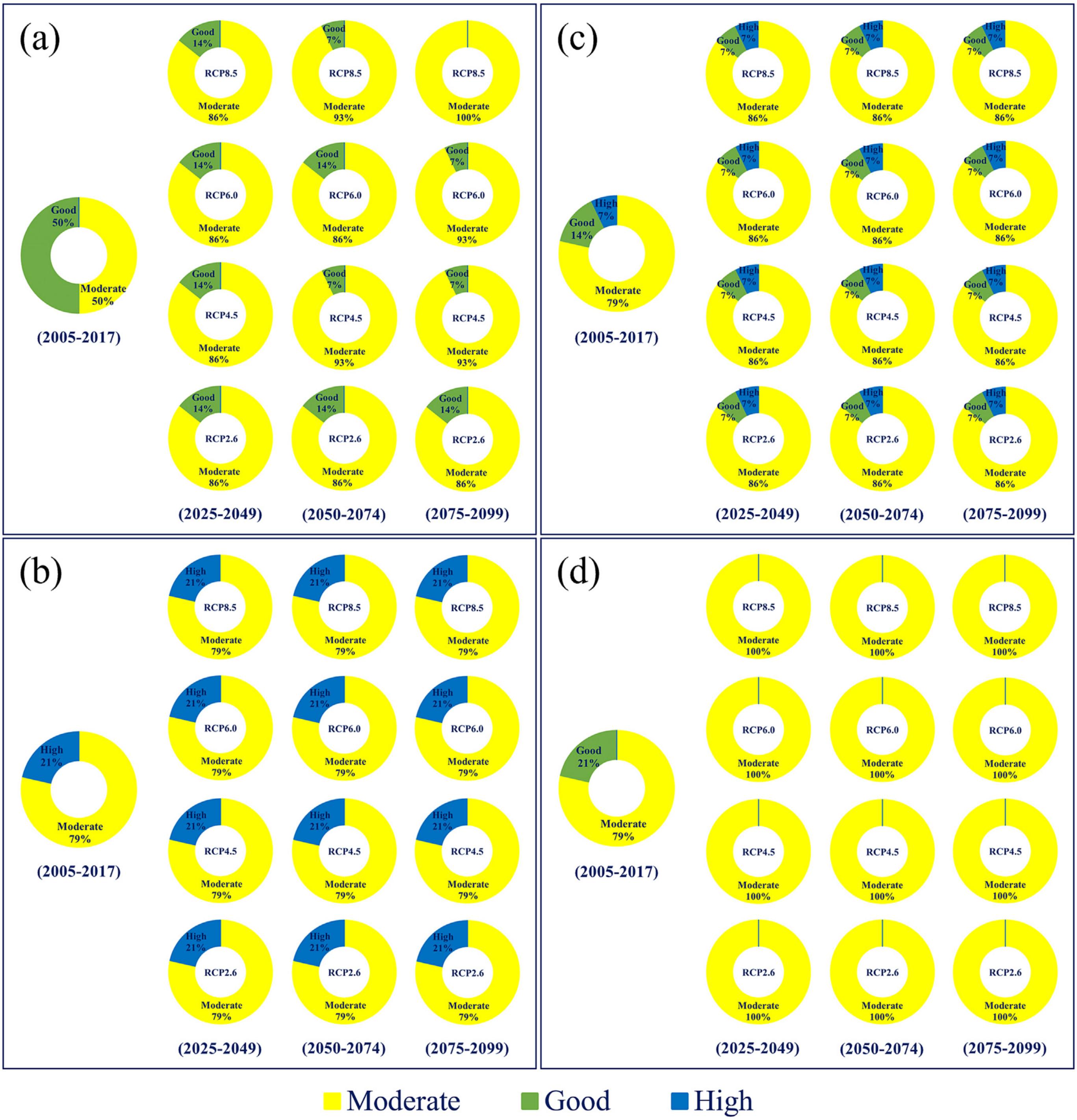

Fig. 6. Nitrate (a), ammonium (b), total phosphorus (c), and chemical (d) status of 14 representative sites in baseline and future periods for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios according to the Spanish Royal Decree 817/2015.

total phosphorus (hydrologic parameter uncertainty: 0.09 mg N/l, GCM uncertainty: 0.03 mg N/l, and emission uncertainty: 0.03 mg N/l), and IBMWP (hydrologic parameter uncertainty: 2.00, GCM uncertainty: 1.78, and emission uncertainty: 1.29), suggest that the hydrologic and GCM uncertainties are comparable for discharge and IBMWP. While for N and P, hydrologic uncertainty is the highest. Thus, the choice of the parameter values that describe the hydrologic properties of the catchment can affect the model predictions to an extent that is comparable or higher to the uncertainty of GCM predictions. This finding differs from that of Bennett et al. (2012) reporting that the most significant influence on uncertainty of runoff projections in three watersheds in British Columbia is exerted by GCMs, followed by emissions scenarios and then hydrologic parameterizations. Similarly to the approach of Bennett et al. (2012), Table 2 reports the range of GCM uncertainties under the same RCPs. The table also reports the range of emission uncertainties for each GCM. The comparison of the values in Table 2 shows that GCM uncertainties are generally larger than emission uncertainties, that is in agreement with Bennett et al. (2012). Table S4 in the Supplement also presents the quantified hydrologic parameter uncertainties under each combination of GCM and RCP.

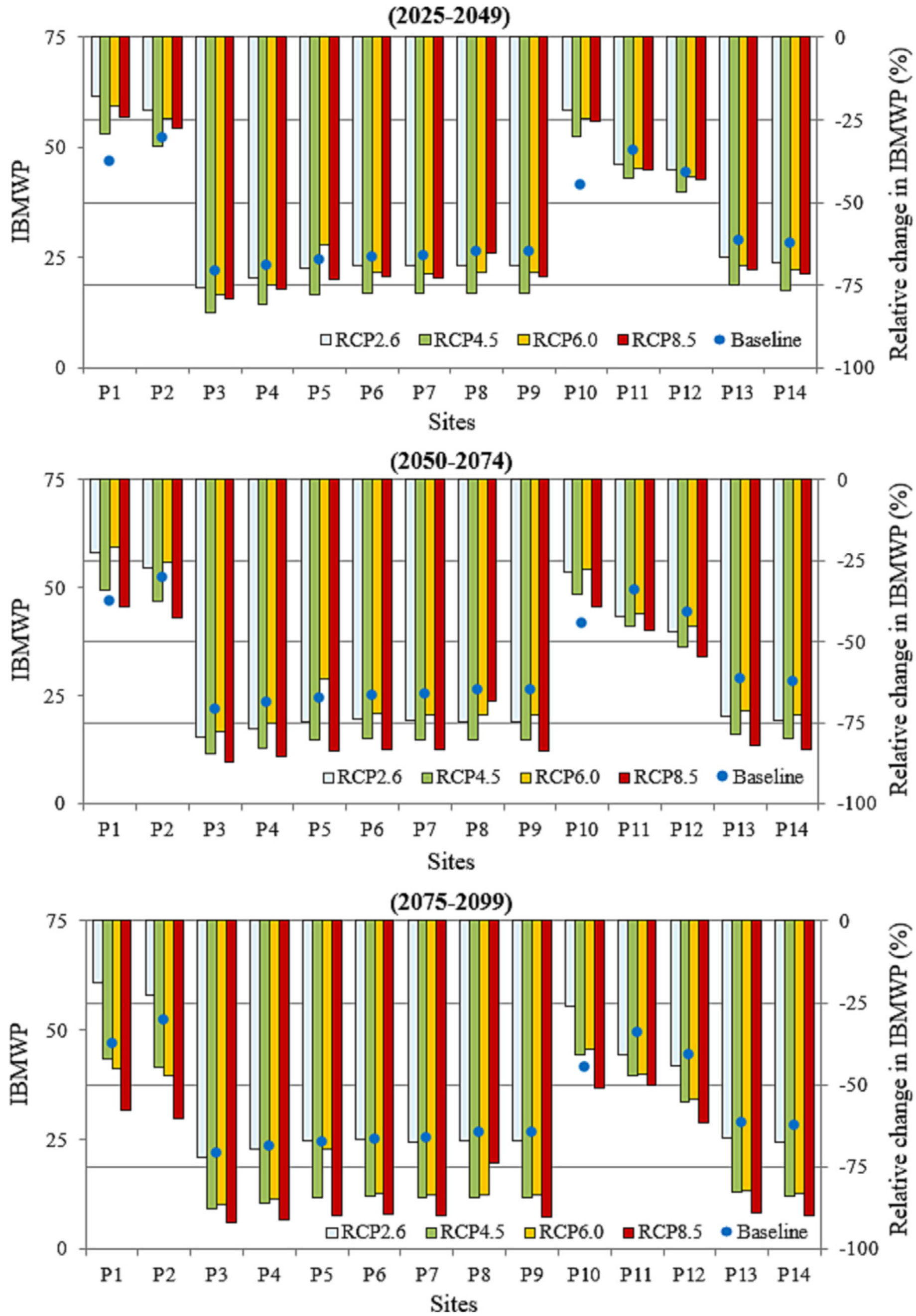

Fig. 7. Change in average IBMWP values (%) at 14 representative sites compared to the baseline (2005–2017) using ensemble of five GCMs for the Near Future (2025–2049), Mid Future (2050–2074), and Far Future (2075–2099) for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios.

3.5. Predicted ecological status

Based on predicted chemical and biological status and "OOAO" principle, it is calculated that the ecological status of most representative sites will worsen in the future compared to the baseline (Fig. 9, and Table S5 to Table S9 in the Supplement). For sites P1, P2, P10, and P11, the ecological status will remain poor under different scenarios except for the RCP8.5 scenario projecting bad status for all sites in the Far Future. The findings of this study are consistent with previous reports on the potential effects of climate change on freshwater ecosystems (Jeppesen et al., 2011; Mantyka-Pringle et al., 2014; Kakouei et al., 2018), particularly with the study predicting that the good ecological status of several EU rivers may be downgraded in future because of climate change, with more vulnerable sites located in Mediterranean countries (Abily et al., 2021).

Interestingly, future nutrient loads in the Bellús Reservoir (located at downstream of the site P14) from the Albaida River are projected to be approximately similar to the baseline period (with a slight reduction tendency; Table S10 in the Supplement). However, a possible worsening of the ecological status of the reservoir is predicted for the future in case of a reduction in the volume of water stored in the reservoir due to increased evaporation and lower water availability, which would result in higher nutrient concentrations and increased eutrophication. This prediction agrees with Rocha et al. (2020), which states that climate change would negatively impact water quantity and quality in reservoirs. Other studies also reported higher concentrations of P and N in warm arid lakes during dry periods (when the water table is low) despite lower external nutrient loads due to enhanced evapotranspiration and decreased inflow (Özen et al., 2010; Jeppesen et al., 2011). Thus,

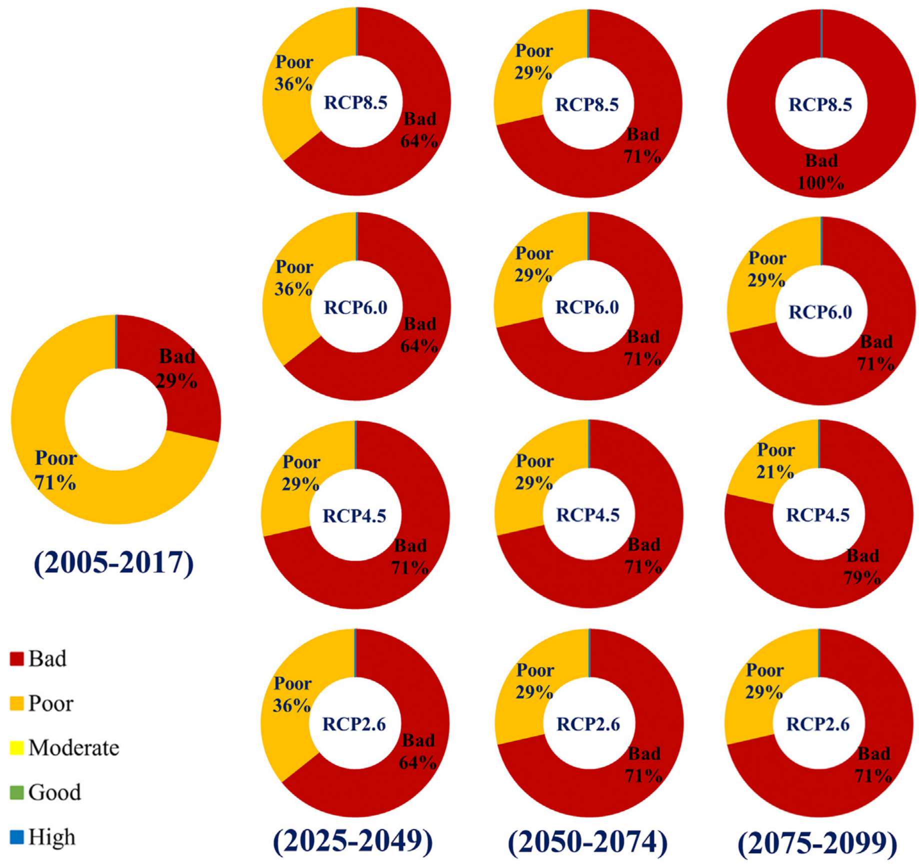

Fig. 8. Biological status of 14 representative sites in baseline and future periods for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios according to the Spanish Royal Decree 817/2015.

the improvement of WWTPs providing high-quality effluents and the sustainable management of agriculture with less nutrient loss to surface waters should be implemented in the valley to reduce the external nutrient load.

4. Conclusions

A SWAT-based ecohydrological modeling framework was used to investigate potential impacts of climate change on ecological status of Albaida Valley Rivers network using climate projections of five GCMs and four emission scenarios. Despite the different emission scenarios, Albaida Valley is expected to face rising temperature, reduced precipitation and discharge, and downgrading of ecological status. These findings emphasize the urgent need for scientifically informed decisions to manage and preserve freshwaters and address the importance of climate change mitigation and adaptation measures at the local, national, regional, and global levels. Even in case mitigation actions are implemented (e.g., for RCP2.6), this study projects that rivers may experience a lower ecological status even in the most optimistic scenario (RCP2.6). This suggests that adaptation measures (e.g., improving treatment of wastewater and/or adopting fertilizer management strategies to reduce nutrient leaching) will be necessary to avoid this situation. In addition, the uncertainty analysis performed in this

Table 2

GCM and emission uncertainties for projections of discharge (m^3/s), nitrate (mg N/l), ammonium (mg N/l), total phosphorus (mg P/l), and IBMWP.

	GCM uncertainty				
	Under RCP2.6	Under RCP4.5	Under RCP6.0	Under RCP8.5	
Discharge	0.11	0.06	0.09	0.07	
Nitrate	0.34	0.39	0.50	0.51	
Ammonium	0.05	0.05	0.06	0.06	
Total phosphorus	0.02	0.03	0.03	0.03	
IBMWP	2.18	1.27	2.38	1.71	
	Emission uncertainty				
	For GCM1	For GCM2	For GCM3	For GCM4	For GCM5
Discharge	0.03	0.06	0.07	0.02	0.02
Nitrate	0.44	0.31	0.39	0.43	0.37
Ammonium	0.03	0.03	0.03	0.01	0.01
Total phosphorus	0.03	0.04	0.04	0.03	0.03
IBMWP	1.24	1.70	2.30	1.00	0.71

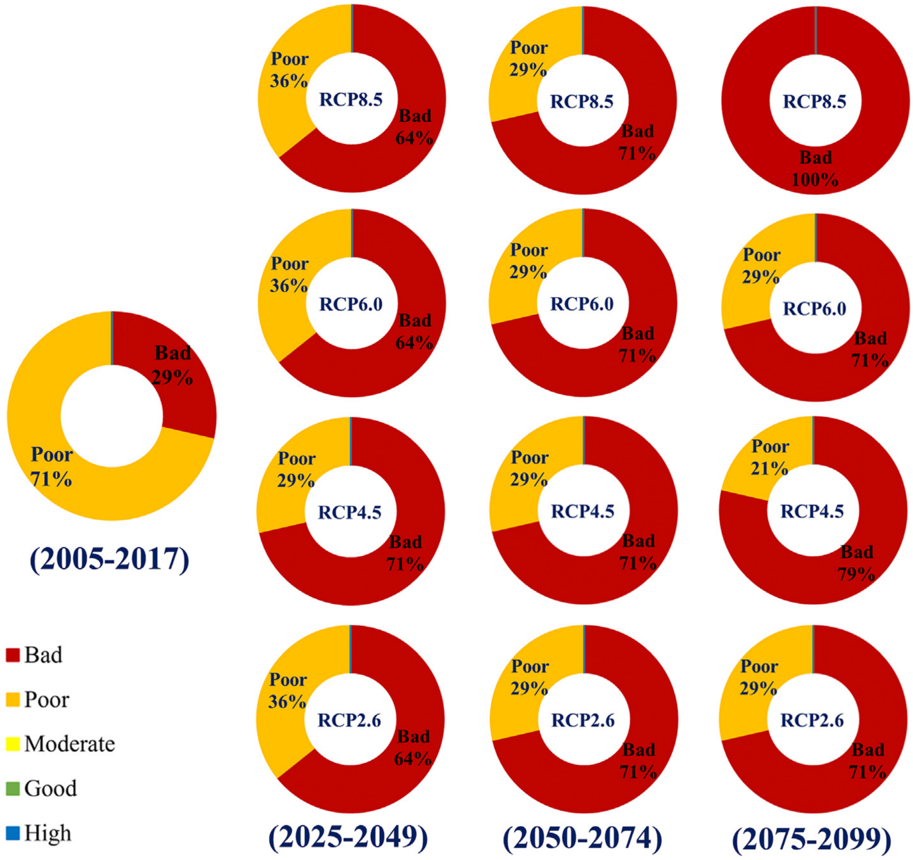

Fig. 9. Ecological status of 14 representative sites in baseline and future periods for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios using projected chemical and biological status and according to the Spanish Royal Decree 817/2015.

study reveals that the parameter values that characterize the catchment's hydrological features might have an equivalent level of impact on model predictions as GCMs, which this demonstrates the importance of characterizing the uncertainties from both hydrologic models and climate projections in climate change impact assessments. The modeling approach provided in this study could be generally used in different watersheds to investigate possible effects of changes in climate, land use and local management policies on freshwater ecosystems.

CRediT authorship contribution statement

Hamed Vagheei: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Alex Laini:** Conceptualization, Methodology, Writing – review & editing. **Paolo Vezza:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Guillermo Palau-Salvador:** Conceptualization, Methodology, Writing – review & editing. **Fulvio Boano:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164645.

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